March 22, 1999

Dr. Allan H. Treiman, Ph.D.

Mr. Edward Heffernan
Associate Administrator for Legislative Affairs
NASA HQ

Dear Mr. Heffernan:

In March 1998, Mr. Michael Moore of Amarillo TX wrote to the Hon. P. Gramm, the Hon. K.B. Hutchison, and the Hon. M. Thornberry about a rock he believes to be a meteorite from Mars. He requested that the government investigate this rock, which he calls the Frass rock, for its potential importance to the space program. You forwarded their concerns to Dr. D. Black, Director of the Lunar and Planetary Institute, and the matter was forwarded to me. I am expert on martian rocks, and so am competent for this investigation.

To evaluate Mr. Moore's claims, I have applied usual and customary tests for determining if a rock is a meteorite, and for determining what planetary body a rock may have come from. The standard for recognition as a meteorite is comparison of its surface texture with those of known meteorites. The standards for a Martian origin are data on Mars rocks and soil acquired by the Viking and Mars Pathfinder spacecraft, and data on the recognized martian meteorites. The martian meteorites themselves are accepted as martian by comparison with Viking lander spacecraft analyses of Mars rocks, soil, and atmosphere. During this inquiry, I examined the Frass rock in Mr. Moore's presence, received samples of the rock from him, and received results of chemical and age analyses of the Frass rock which he had purchased. Further, I examined the Frass rock with optical microscopy, and studied the chemical analyses in relation to published analyses of Earth rocks and meteorites.

I have found no evidence that the Frass rock is a meteorite, and no evidence that it came from Mars. The results of every test on the Frass rock are consistent with an Earthly origin, and many results are definitely not consistent with a martian origin. Mr. Moore stated that the Frass rock appeared between one day and the next on his aunt's ranch. I cannot say how the rock came to rest where it was found, but (again) there is no evidence that it came from off the Earth, and no evidence that it came from Mars.

The following appendix includes the factual bases for my conclusions. I include four copies of the appendix for distribution to Mr. Moore's Senators and Representative. I have also mailed a separate copy to Mr. Moore. If explanations or further details are needed, I will be happy to assist.

Sincerely;

Allan H. Treiman, Ph.D.
Senior Staff Scientist
Lunar and Planetary Institute

INVESTIGATION OF THE POSSIBLE MARTIAN ORIGIN OF THE "FRASS ROCK" OF MR. MICHAEL MOORE, AMARILLO, TX.

by

Allan H. Treiman
Senior Staff Scientist
Lunar and Planetary Institute
Houston, TX

March 22, 1999

EXECUTIVE SUMMARY

Mr. Michael Moore of Amarillo Texas reported to his Senators and Congressman that he possessed a meteorite from Mars, and requested that NASA study the object. His request was forwarded, through the NASA Legislative liaison officer, to Dr. Allan H. Treiman of the Lunar and Planetary Institute, TX. Dr. Treiman is an expert on martian meteorites.

The object, a rounded boulder of bubbly basalt lava rock, is not a meteorite and is not from Mars.

The boulder cannot be considered a meteorite as it shows no fusion crust, the glassy melted coating that develops on all rocks from space as they burn through the Earth's atmosphere.

Although the known martian meteorites are basalt lava rocks (or closely related), Mr. Moore's basalt rock is not martian; it is from the Earth. This conclusion is based on chemical elemental analyses of the rock. With the available chemical data, ten distinct tests a basalt's planetary origin could be applied to Mr. Moore's basalt. None of the tests suggests that the rock formed on Mars; all of the tests show that it is similar to Earth basalts, and so must have formed on Earth.

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1. History of this Investigation

Mr. Moore reports having found the Frass rock in the 1970s on his aunt's ranch, near Canadian TX. He reports that the rock was found one day on their usual rounds of the ranch, in a spot where no rock had been the day before. He collected the rock at that time, and has kept it since. No other people were present to corroborate the rock's appearance; unfortunately, his aunt has passed on. Starting in 1997, Mr. Moore reports having a renewed interest in the rock after hearing about the possible find of evidence for martian life in a martian meteorite. He had shown the Frass rock to a number of scientists (at Texas Tech, West Texas A & M, and University of Arizona), and felt frustrated that they did not concur that it was a meteorite and did not adequately address his claims. To substantiate his claims about the rock, Mr. Moore hired an analytical laboratory, Geochron Laboratories (Cambridge, MA) to obtain potassium-argon age dates on fragments from the Frass rock; those analyses were reported on 31-Dec-97 and 9-Jan-98 (Table A1). Mr. Moore also hired another laboratory, Chemex Labs (Sparks, NV), to do chemical element analyses of fragments of the Frass rock and of sand that had come from it; those analyses were completed on 4-Feb-98 and 13-May-98 (Table A2).

On March 30, 1998, Mr. Moore wrote letters to his congressman (Hon. Mac Thornberry) and his senators (Hon. P. Gramm and Hon. K.B. Hutchison) describing the rock, asking that the rock receive a "complete hearing," and asking that his request be forwarded to NASA. In April 1998, his letters were forwarded to NASA's Associate Administrator for Legislative affairs, who the forwarded the request for a hearing to Dr. Virgil Sharpton, then at the Lunar and Planetary Institute. Dr. Sharpton left the Institute in August 1998, and the request was forwarded to me.

Mr. Moore and I have corresponded by e-mail about the Frass rock, starting in about March, 1997, long before I became involved in this inquiry. In our correspondence, I advised Mr. Moore of the usual and customary criteria for ascertaining that a rock is a meteorite, but did not see the rock and formed no opinion on its nature or origin. I communicated briefly with Drs. David Kring and Jamie Gleason of the University of Arizona about the Frass Rock, who had interviewed Mr. Moore and had seen the rock. They believed the rock to of Earthly origin, and they loaned me a thin section (microscope slide) they had prepared from a fragment of the Frass rock.

On January 19, 1999, Mr. Moore brought the Frass rock to the Lunar and Planetary Institute for me to examine. I did so, and we discussed the rock and its history at some length. Mr. Moore provided additional samples for study, and verified that a microscope slide I had received from researchers at the University of Arizona was indeed of the Frass rock.

2. The Frass Rock.

The Frass rock is a rounded fragment of vesicular (bubbly) basalt lava rock, the most common kind of lava erupted from volcanoes. In color it is slightly reddish gray. A portion of the surface appears slightly redder than the rest. Physically, the rock is ellipsoidal, approximately 28 cm by 28 cm by 24 cm (Figure 2.1). On one surface of the rock is a cleft where the rounded surface curves inward ~ 5 cm. The exterior of the Frass rock is rough, exposing countless bubbles (Figure 2.2). The largest bubble is 3 cm long, and most are ~ 1 cm long. In one swath across the surface, the bubbles appear to be aligned, longer than wide, and elongate in the same direction.

Figure 2.1. The Frass Rock.

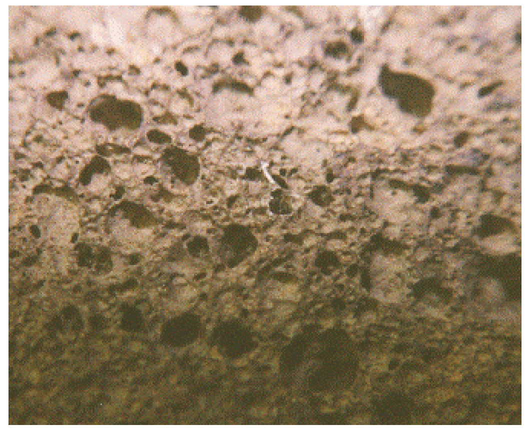

Figure 2.2. Innumerable bubbles on surface of Frass Rock, ~ 5 cm across.

Most of the surface of the rock is bubble holes and the broken edges of basalt rock between them (Figure 2.2). Broken edges of the rock are brownish and coated with dust. A few small areas (a few mm diameter) of smooth coating are visible. This coating is reddish black and slightly iridescent; I could not see any detectable thickness to the coating, and estimate that it is less than 0.05 mm thick. Other materials on the rock's surface and in bubble holes and clefts include: dust; fibers from fabric (red, blue, yellow, white); avian excrement (so identified to me by Mr. Moore); rounded droplets of grayish metal (which appeared like splashes of solder); organic fibers like roots or algae; a white fibrous closed structure, ~3 mm diameter, that looks like a spider egg-sack; and fragments of beetles and a spider (collected and so identified by Mr. Moore).

By appearance, most of the volume of the rock is bubbles; its structure could be compared to the plastic and bubbles in a piece of Styrofoam. The Frass rock, according to Mr. Moore, weighs approximately 22 lbs., which implies an average density of approximately 1.1 gram per cubic centimeter. Solid basalt rock has a density of about 3 grams per cubic centimeter, which implies that the Frass rock is approximately 1/3 basalt rock and 2/3 bubble spaces, filled with air. This proportion seems reasonable from the highly vesicular, nearly frothy appearance of the surface and the interior (Figs 2.2, 2.3).

Many of the vesicles (bubbles) near the surface of the Frass rock are filled with reddish or tan material, which consists of angular grains of quartz sand (to ~ 200μm diameter) in a very fine-grained (<20 μm) mixture of clays, hematite (bright red), and calcite (Figure 2.4). In one area, the clay/calcite mixture is roughly banded. Based on a core sample prepared by Mr. Moore, the interior vesicles appeared to have no sand, and much less clay/carbonate than those on the outside.

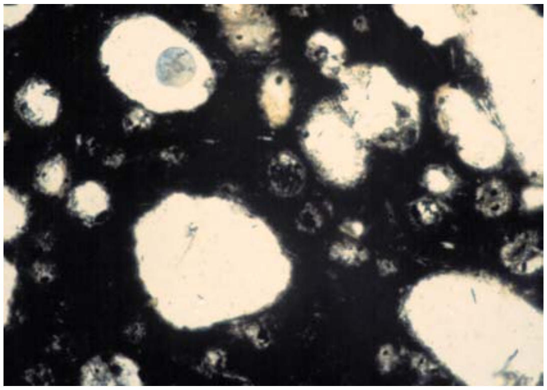

Figure 2.3. Thin section (microscope slide) view of Frass Rock. Five mm across, plane polarized light. Dark areas are basalt rock; bright areas are bubbles.

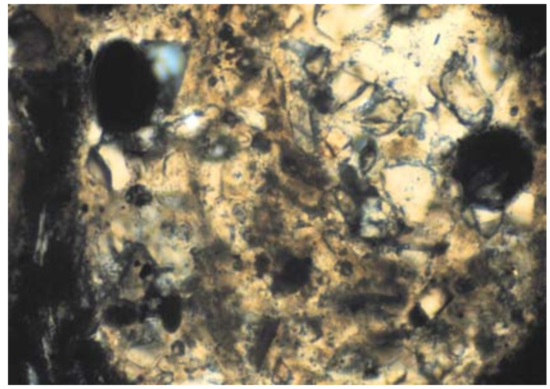

Figure 2.4. Sand filling a bubble in the Frass Rock. 0.75 mm across, plane polarized light. Central area is bubble, filled with angular grains of quartz sand is tan-colored clay plus calcite. Dark areas to left and upper and lower right are basalt rock; to left, note aligned feldspar crystals (gray).

The Frass rock was examined in a microscope slide, i.e. thin section (Figs. 2.3, 2.4). It consists of small grains (to 0.1 mm long) of the minerals pyroxene and plagioclase in a matrix of glass and very fine grained iron oxide minerals (<0.01 mm diameter). These minerals are typical of basalt rock. The pyroxene is slightly yellowish, has inclined extinction, and is probably mostly clinopyroxene. The plagioclase laths are commonly twinned according to the 'plagioclase' or 'sanidine' laws. Both minerals are commonly aligned in the glass. The iron oxide minerals are reddish, and so are probably hematite.

Mr. Moore has provided chemical analyses, purchased commercially, of the Frass rock. These analyses are tabulated under Supplementary Material. The two analyses of the bulk rock, labeled Red and Gray rock, are characteristic of basalt and are fully consistent with the microscopic examination (above). Specifically, the Frass rock would be classified as an alkaline basalt or trachybasalt (Figure 2.5).

Mr. Moore purchased three potassium-argon (K-Ar) age determinations of the age of crystallization of the Frass rock. These ages range from 49.0 million years to 12.9 million year. The oldest age was from the coarser fragments (+80 mesh = larger than 0.17 mm), which had the same potassium content (2.4% K_2O) as the basalt (see Supplementary Material). The younger ages came from the finer fragments (–80+325 mesh = 0.04 to 0.17 mm), which had less potassium (2.2% K_2O).

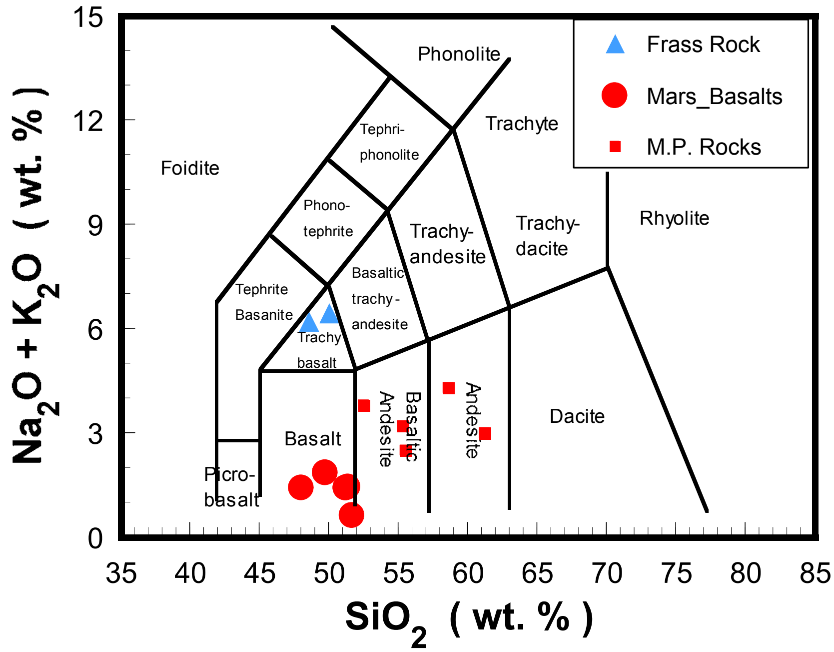

Figure. 2.5. Igneous Rock Classification Scheme of the IUGS (International Union of Geophysical Sciences). Martian basalts are the martian meteorites; Mars Pathfinder rocks (M.P. Rocks) compositions from Rieder et al. (1997).

INTERPRETATION.

The Frass rock is a boulder of a vesicular basalt rock, which probably crystallized 49 million years ago. Its igneous minerals and textures are typical of basalt. The presence of hematite rather than magnetite as the iron oxide mineral suggests that the rock was oxidized after it formed – possibly in a soil environment. The presence of quartz sand, clay, and carbonate minerals in the rock's vesicles also suggest that the rock resided in a soil environment. The younger K-Ar ages, being of fine material and having less potassium than the bulk rock, may reflect contamination with this sand/clay mixture. The weathering minerals are consistent, in general, with expected surface materials at or near its find site near Canadian, TX; quartz sand is abundant in ancient sand dunes in the area, and west Texas is famous for its caliche soils, cemented with carbonate and clay. However, lacking reference samples of soil and sand from the area, I cannot confirm or deny this idea.

3. Is the Frass Rock a Meteorite?

Regardless of how the Frass rock came to be found on the ranch near Canadian, Texas, one must ask whether it is a meteorite or not. Norton (1994) and Kring (1998) give the accepted characteristics of freshly fallen rock meteorites: coating by a glass layer, the fusion crust; and an aerodynamic shape and/or rounded edges and corners. Both shape and fusion crust arise as the meteorite passes through the Earth's atmosphere.

Meteorites speed into the Earth's atmosphere faster than 11 kilometers per second. This is the absolute minimum speed for a meteorite that was not in orbit around the Earth; objects in orbit around the Earth, like the Space Shuttle, enter the atmosphere going somewhat slower. But meteorites usually enter the atmosphere going much faster, nearer to 40 kilometers per second. When this speeding meteorite hits the Earth's atmosphere, it heats up to glowing by friction with the atmosphere – this glow is the light of a meteor in the night sky. As the meteorite "burns" through the Earth's atmosphere, its sharp edges concentrate the heat and are melted or vaporized off, leaving the rock rounded or aerodynamically shaped (Figure 3.1). The surface of a meteorite gets so hot that it melts, above about 1100°C for a basaltic meteorite. This molten surface, when it cools, becomes the fusion crust (the word "fusion" is used here to mean melting); Figure 3.1 shows the fusion crust on a martian meteorite. The fusion crust is noticeably thick, on average about 1 millimeter, but can be as thin as 0.25 millimeter and as thick as a few mm (Norton, 1994). Many freshly fallen meteorites are completely covered in fusion crust. Other meteorites have broken in the air after the fusion crust has cooled, and have rounded surfaces covered by fusion crust and rough angular surfaces without fusion crust.

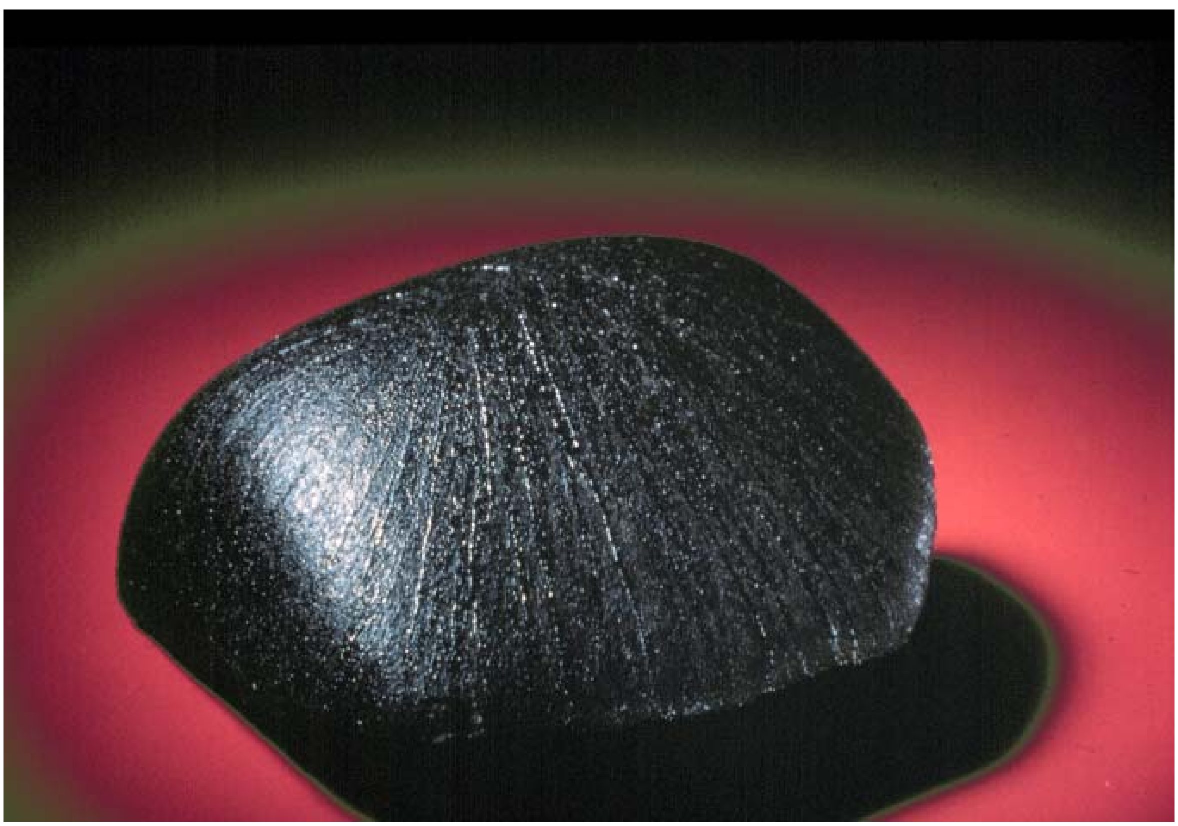

Figure 3.1. Black glass fusion crust on the Lafayette meteorite (Martian). Meteorite is 4.5 cm across. Image courtesy of The Smithsonian Institution.

Does the Frass rock satisfy these criteria for being a freshly fallen meteorite? First, its rounded ellipsoidal shape (Figure 2.1) is roughly consistent with being a meteorite, but does not prove that it is a meteorite. Rocks with rounded shapes can form by many other processes. I am concerned that its surface shows so many sharp edges (Figure 1.2), as I would expect that the heat of entering the atmosphere would have removed them.

Second, does the Frass rock have a fusion crust? In my opinion, no. The vast majority of the Frass rock's surface is like Figure 2.2 – rough angular edges of vesicles (bubbles). The rock is not covered, completely or in part, by fresh glass, such as is seen on freshly fallen meteorites (Figure 3.1). A few spots on the meteorite, in aggregate less than 1 square centimeter, are covered by a smooth dark coating (as described above). But this coating is significantly thinner than recognized fusion crusts, and so must be considered questionable. To me, these patches of dark coating on the Frass rock look like desert varnish, a black coating that grows on rocks in desert environments.

Based on this data, I conclude that the Frass rock is not a meteorite. My principal criterion is that the Frass rock does not show the definitive surface structure, the fusion crust, observed on all freshly fallen meteorites. Mr. Moore does not agree with this opinion, and has stated that the Frass rock is so unusual that it need not be held to the same criteria one would apply to normal meteorites. In my opinion, the chemical composition of the Frass rock is similar enough to those of known basalt meteorites, with thick glassy fusion crusts (Figure 3.1) that it too ought to have developed a thick glassy fusion crust if it had passed through the Earth's atmosphere from interplanetary space.

4. How to Test if a Rock is from Mars

The Frass rock is basalt, a rock formed by the solidification of molten lava. This is fortunate, because the chemical composition of a basalt contains significant clues about which planet it formed on (Drake, 1980). Except for some tests of isotope abundances, these chemical composition tests are the most useful in distinguishing basalts from different planets.

Basalt lava is common on rocky planets and moons in the Solar System. On Earth, the sea floors, ocean islands, and most volcanoes are made of basalt lava. The dark areas on the Moon, the mare, are plains of solidified basalt lava, and the materials of the lunar highlands formed from basalt lava. Venus is covered by plains of basalt lava (analyzed in place by Russian landers), and has many volcanoes thought to be made of basalt. The martian meteorites are all basalts or formed from basalt lavas; the chemical analyses of martian materials from the Viking and Mars Pathfinder spacecraft are all basalt or material derived from basalt. Many meteorites from asteroids are basalt.

Basalts from all these planets (and asteroids) can appear nearly identical. Nearly all contain the same minerals: pyroxenes, feldspars, olivine, iron-titanium oxides. All can have similar internal textures (how the mineral grains fit together) and structures, like an abundance of bubbles or holes.

However, basalts from different planets can have distinctly different abundances and ratios of some chemical elements. The specific, useful elements and element ratios have been discovered over the last 30 years by comparing Earth basalts, lunar basalts (returned by Apollo astronauts), and the several types of basalt meteorite, including the meteorites now known to be from Mars. These differences in element abundances are the bases for tests of whether a basalt meteorite is from Mars.

These tests all rely on comparing abundances, in basalts, of pairs (or groups) of elements that behave similarly during formation and crystallization of basalt lavas, but behaved differently during ancient, planet-wide events. As an instance, the elements nickel (Ni) and magnesium (Mg) behave very similarly during the formation and crystallization of basalt lavas. But Ni readily mixes with iron metal into a planet's iron core, while Mg remains entirely outside the core, in the rocky part of the planet. In this way, the Ni/Mg ratio of a basalt shows something about the formation of its planet's core. As each planet has a different overall chemical composition, and each experienced a different history of core formation, the Ni/Mg ratio may be different for each planet or asteroid. As another instance, the elements rubidium (Rb) and lanthanum (La) behave nearly identically during formation and crystallization of basalt. When planets originally formed from gas and dust, however, Rb was more likely to stay in the gas than was La, and so was less likely to be incorporated into a solid planet. In this way, the Rb/La ratio of a basalt shows something about the gas and dust that went into forming the planet.

The *available tests are only applicable to basalt lava rocks* and to closely related rocks like andesites. For the Frass rock, this means that only analyses of Gray Rock, Red Rock can be used. These tests are *not applicable to other kinds of rocks*, like sandstone, limestone, or granites. We have no samples or analyses of rocks like these from other planets, and so have no basis for comparison and testing. Also, these tests are *not applicable to mixed materials*, like Mr. Moore's analyses labeled 'sand 1,' 'sand 2,' and 'sand 3.' These mixed analyses are discussed in Section 6.

5. Is the Frass Rock from Mars?

5.1 Results of Tests

Table 5.1 summarizes the results of all available chemical tests of whether the Frass rock formed on Mars. These tests imply that the Frass rock did not form on Mars. All of the tests are consistent with the Frass rock forming on Earth. Five of the chemical tests (#s 1, 2, 4, 9, & 10) imply unambiguously that the Frass rock did not form on Mars.

Table 5.1. Summary of Results of Chemical Tests

		Implications for Frass Rock		
	Chemical Test	Implies a Martian Origin	Ambiguous (X), or Possibly Ambiguous (?)	Implies an Earthly Origin
1.	FeO vs. MnO			X
2.	Ni vs. Mg			X
3.	Co vs. (FeO+MgO)		X	
4.	Cr vs. Mg#			X
5.	Mg/Si vs. Al/Si		?	X
6.	K vs. La		?	X
7.	Rb vs. La		?	X
8.	Cs vs. La		?	X
9.	Ga vs. Al			X
10.	TiO_2 vs. Al_2O_3			X

For a given test, "Implies an Earthly Origin" means that the Frass rock is indistinguishable from Earth basalts, and significantly different from Martian basalts (the martian meteorites and the Viking and Mars Pathfinder chemical analyses). "Implies a Martian Origin" would mean that the Frass rock is indistinguishable from Martian basalts and significantly different from Earth basalts. "Ambiguous" means that the given test does not show the Frass rock to be clearly Earth-like or clearly Martian. "Possibly Ambiguous" means either that: 1) the Frass rock could conceivably appear to be Martian or Earthly if more chemical analyses were available; or 2) the test, although accepted and in the scientific literature, may not be definitive for all Earth rocks.

Short explanations of these tests, and graphs of their results, are given below. Chemical analyses of martian basalts are from the literature, as quoted in Meyer (1998); analyses of Mars Pathfinder rocks and soils are from Rieder et al. (1997), Wänke (1999), and Dreibus et al. (1999); analysis of Viking soil is from Clark et al. (1982); and analyses of Earth basalts are from BVSP (1981), Barnes et al. (1983), Dungan et al. (1989), and Puchtel et al. (1996).

5.2 FeO vs. MnO

The proportion of iron to manganese, Fe/Mn, in basalts differs from planet to planet (Laul et al., 1972a, 1986; Wänke et al., 1973; Stolper et al., 1979; Drake et al., 1989). Iron and manganese behave nearly identically in the formation and crystallization of basalt lava – they are distributed more-or-less evenly between the molten lava and the minerals olivine and pyroxene. When a planet forms, iron would have been more likely to accumulate onto the planet than manganese (some of which would have remained in the gas). When a planet's core forms, much more of the planets' iron goes into the core than does its manganese.

For basalts, the Fe/Mn ratio is usually graphed as masses of Fe and Mn in per cent of the rock, calculating both as if they were the oxides FeO and MnO (the standard in chemical analyses of geological materials). Figure 5.2 shows that FeO and MnO abundances in the Frass rock fall squarely with Earth basalts, and are not consistent with martian meteorites nor with materials analyzed on Mars.

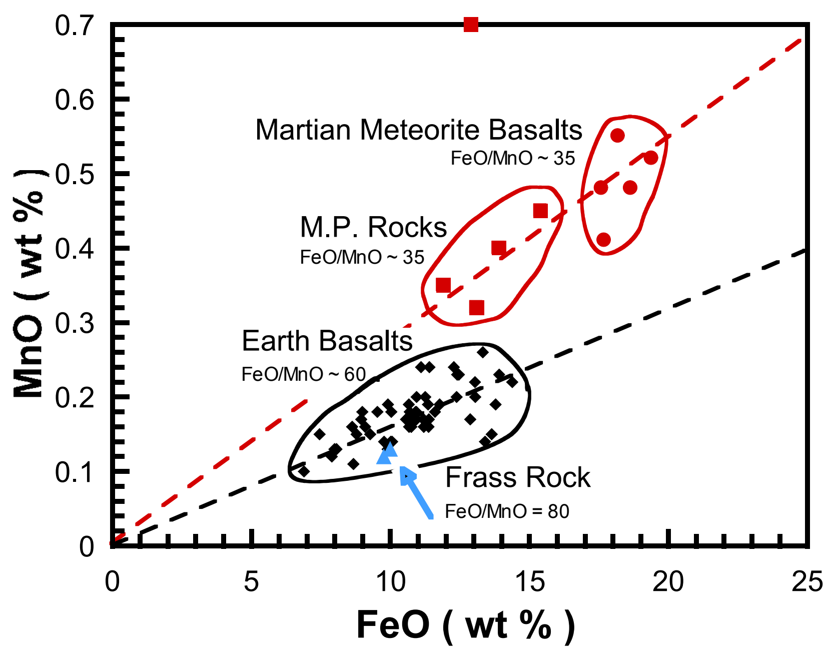

Figure 5.2. Abundance of manganese (Mn) and iron (Fe), graphed as equivalent masses of oxides (MnO and FeO), for the Frass rock, martian meteorites, rocks at the Mars Pathfinder site (M.P. Rocks), and reference basalts from Earth. Iron in the Frass rock, analyzed as Fe_2O_3, is recalculated as FeO. The red lines enclose martian basalt meteorites and Mars Pathfinder rocks; the black encloses Earth basalts. On this diagram, the Frass rock falls in the Earth basalt field, significantly different from martian meteorites and Mars Pathfinder rocks.

5.3. Ni vs. Mg

The proportion of nickel to magnesium, Ni/Mg, in basalts and their minerals differs from planet to planet (BVSP, 1981; Wänke and Dreibus, 1988; Longhi et al., 1992). Nickel and magnesium behave nearly identically in the formation and crystallization of basalt lava – they are preferentially incorporated, to approximately the same degree, into the minerals olivine and pyroxene. When a planet forms, magnesium would have been more likely to accumulate onto the planet than nickel (some of which would have remained in the gas). When a planet's core forms, most of the planets' nickel goes into the core while none of its magnesium does.

For basalts, the Ni/Mg ratio is usually graphed as the abundance of Ni (in parts per million, ppm) versus that of Mg (in per cent). Figure 5.3 shows that the Ni and Mg abundances in the Frass rock are consistent with Earth basalts, and are not consistent with martian meteorites

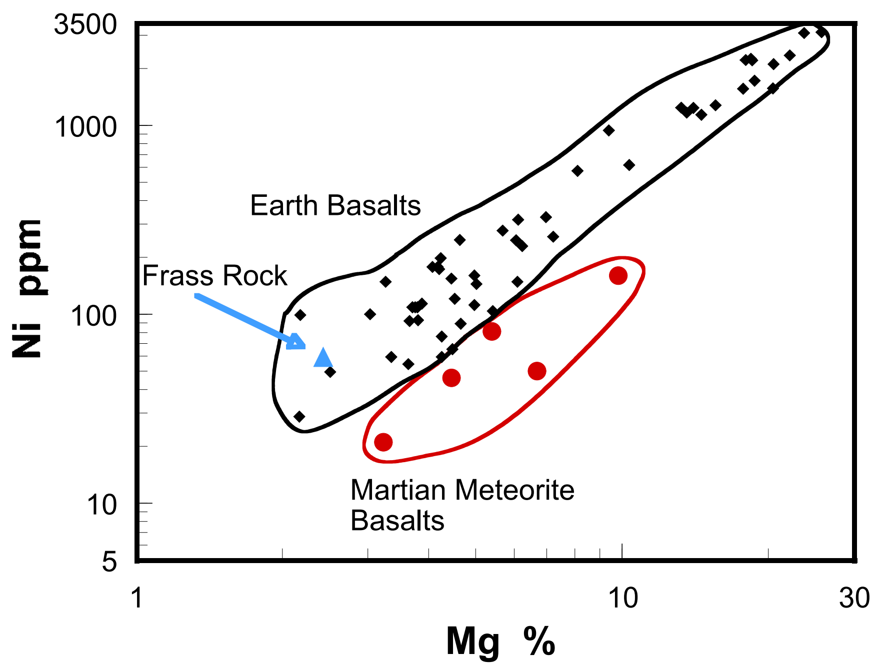

Figure 5.3. Abundances of nickel (Ni) and magnesium (Mg) in the Frass rock, martian meteorites, and reference basalts from Earth. The red line encloses martian basalts; the black encloses Earth basalts. On this diagram, the Frass rock falls cleanly with Earth basalts, and significantly different from martian basalts.

5.4 Co vs. (FeO+MgO)

The proportion of cobalt (Co) to ferromagnesian elements (Fe+Mg) in basalts and their minerals differs from planet to planet (Stolper et al., 1979; Laul et al., 1986; Wänke and Dreibus, 1988; Longhi et al., 1992). Cobalt behaves nearly like a combination of Fe and Mg in the formation and early crystallization of basalt lava – they are preferentially incorporated, to approximately the same degree, into the minerals olivine and pyroxene. This produces a trend, upper-right to lower-left, on the diagram. When iron-titanium oxides begin crystallizing from a basalt magma, the trend on the graph dips nearly straight down (very rapid decrease in cobalt) . When a planet forms, magnesium would have been more likely to accumulate onto the planet than cobalt and iron (some of which would have remained in the gas). When a planet's core forms, most of the planets' cobalt and much of its iron go into the core while nearly none of its magnesium does.

For basalts, Co vs. Fe+Mg is usually presented as the weight abundance Ni (in parts per million, ppm) versus MgO+FeO (in percent). Figure 5.4 shows that Co and MgO+FeO in the Frass rock is consistent with Earth basalts. However, its values here are quite close to the field of analyses of martian basalts. So, I judge that this test is ambiguous, and does not suggest or disprove a martian origin for the Frass Rock.

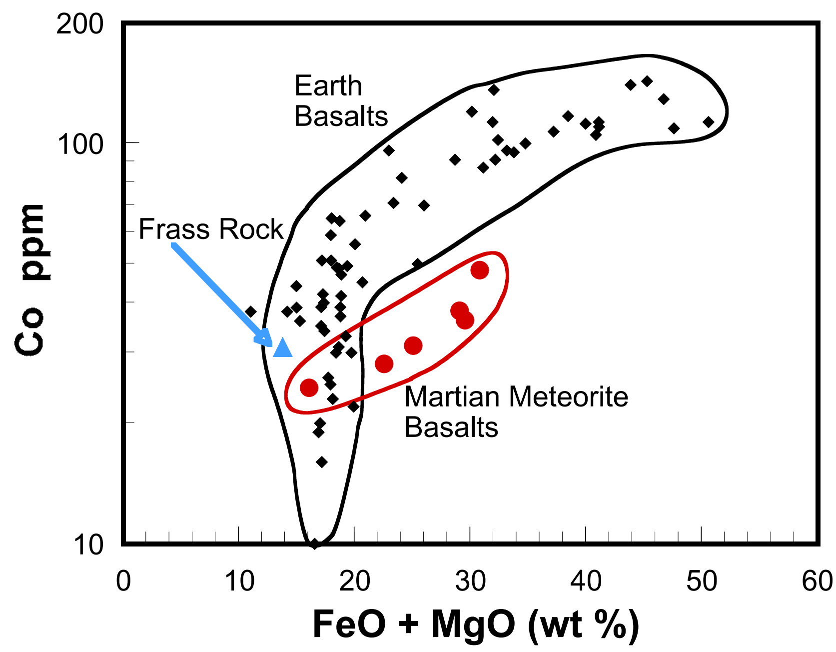

Figure 5.4. Abundance of cobalt (Co) compared to equivalent mass of iron and magnesium oxides in the Frass rock, martian meteorites, and reference basalts from Earth. Iron in the Frass rock, analyzed as Fe_2O_3, is recalculated as FeO. The red line encloses martian basalts; the black encloses Earth basalts. On this diagram, the Frass rock falls in the Earth basalt field, but not significantly distant from the martian basalts.

5.5 Cr vs. Mg#

The proportion of chromium to "ferromagnesian elements," Cr to Fe+Mg, in basalts and their minerals differs from planet to planet (Stolper et al., 1979; BVSP, 1981; Laul et al., 1986; Wänke and Dreibus, 1988; Drake et al., 1989). The abundance of Cr in a basalt changes in a characteristic manner as the basalt's source area (in the mantle) is melted and as the basalt crystallizes. When a planet forms, magnesium would have been more likely to accumulate onto the planet than chromium and iron (some of which would have remained in the gas). When a planet's core forms, much of the planets' iron goes into the core while little chromium and no magnesium do.

This characteristic behavior of chromium is best seen on a graph of Cr abundance in parts per million (ppm) versus the Mg/Fe ratio in the basalt. The latter is given as the "magnesium number," the molar ratio Mg/(Mg+Fe) in the basalt, abbreviated as Mg#.

Figure 5.5 shows that the Cr abundance and Mg# in the Frass rock is consistent with Earth basalts, and is nearly a factor of ten lower than in martian basalts.

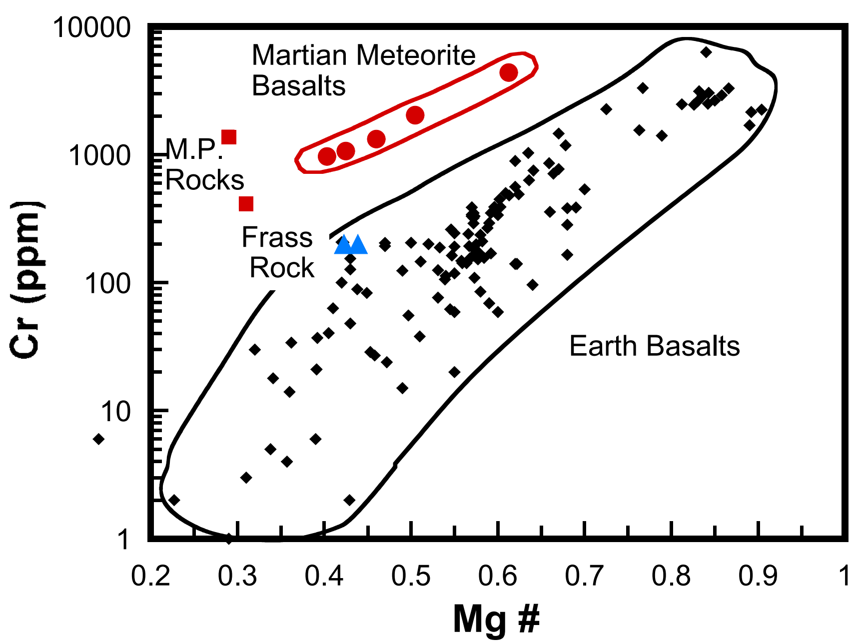

Figure 5.5. Abundance of chromium (Cr) graphed against magnesium number (Mg#) for the Frass rock, martian meteorites, rocks at the Mars Pathfinder site, and reference basalts from Earth. The red field encloses Cr vs. Mg# trend of martian meteorites. The Frass rock falls cleanly within the Earth basalt field, and significantly distant from the martian materials.

5.6 Mg/Si vs. Al/Si

The relative proportions of magnesium, aluminum, and silicon (Mg, Al, and Si) in basalts and in mantle rocks has been used to discriminate among basalts from different planets, and was used by the Mars Pathfinder APX team to illustrate their chemical analyses from Mars in the context of the solar system (Rieder et al., 1997). Abundances of Mg and Al in basalts and mantle rocks tend to vary inversely – the more Al, the less Mg. When a planet forms, magnesium and aluminum would have been more likely to accumulate onto the planet than silicon, more of which would have remained in the gas. In general, basalts from planets with more silicon will plot closer to the origin on this graph (have lower Mg/Si and Al/Si ratios) than basalts from planets with less silicon. However, it is clear that basalts from a single planet can show a wide spread on this graph, as in the range of Earth basalts or the difference between the martian basalts Zagami and QUE94201 (Fig 5.6). In this respect, the Mg/Si vs. Al/Si graph is not particularly useful or characteristic of planetary origin. It is included here only because of it use with Mars Pathfinder and its use by Mr. Moore with respect to the Frass Rock.

As show in Figure 5.6, the analyses of the Frass basalt fall nearly exactly on the Earth line (in black), and quite distant from the Mars fractionation line (in red). Chemical analyses of “sand” from the Frass rock are discussed below in Section 6.

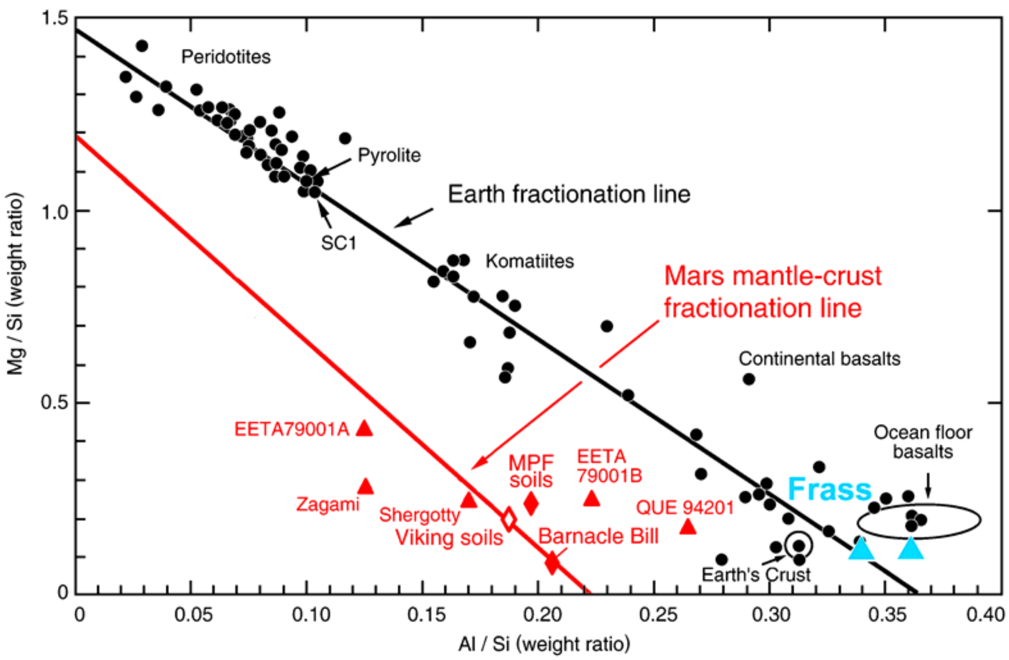

Figure 5.5. Abundance of elements silicon (Si), magnesium (Mg), and aluminum (Al) as the weight ratios Mg/Si and Al/Si in the Frass rock, martian meteorites, rocks at the Mars Pathfinder site, and reference basalts and mantle rocks from Earth (Rieder et al., 1997). On this diagram, the Frass rock plots with Earth basalts.

5.7 K vs. La

The proportion of potassium to lanthanum, K/La, in basalts and their minerals differs from planet to planet (Stolper et al., 1979; Wänke, 1981; Smith et al., 1984; McSween, 1985; Treiman et al., 1986; Wänke and Dreibus, 1988; Longhi et al., 1992). Potassium and lanthanum behave nearly identically in the formation and crystallization of basalt lava – they are excluded nearly completely from solid minerals (olivine, pyroxenes, feldspars) and are concentrated together in the lava. Sometimes, a similar diagram is given as potassium vs. uranium, because uranium and lanthanum behave the same in basalts. When a planet forms, lanthanum would have been more likely to accumulate onto the planet than potassium (some of which would have remained in the gas). The K/La ratio would have not been affected by formation of a planet's core.

For basalts, abundances of K and La are usually given as mass in parts per million, ppm. Figures 5.7 shows that K and La abundances for the Frass rock plot with Earth basalts. The red line marks the K/La ratio for martian basalts. Some Earth basalts plot near or on this line, which means the K/La test is partially ambiguous – not all Earth basalts can be distinguished from Mars basalts using K and La. However, the Frass rock falls distinctly below the red line, suggesting that it is not from Mars.

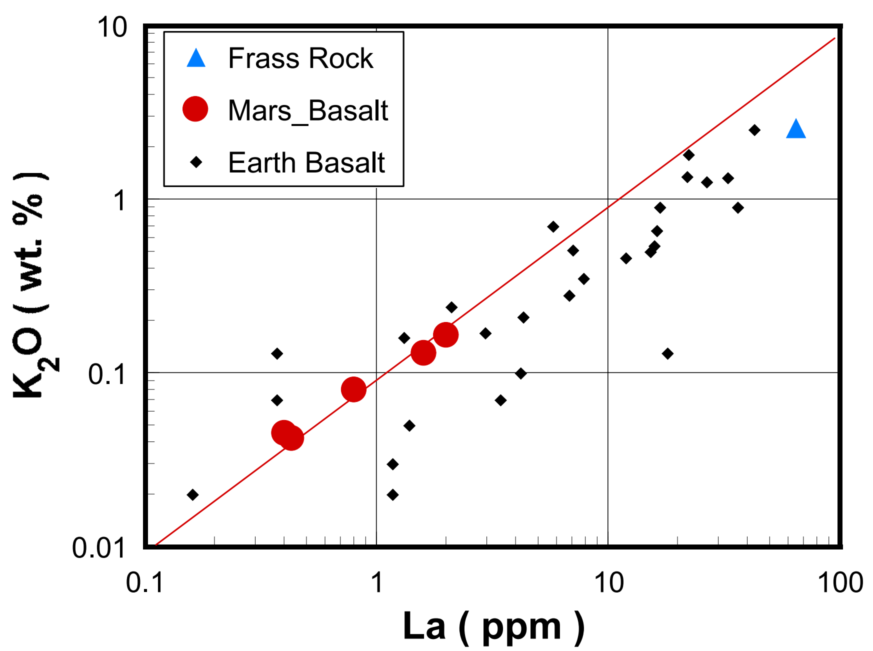

Figure 5.7. Abundances of potassium (K) and lanthanum (La) in the Frass rock, martian meteorites, and reference basalts from Earth. The red line shows the K/La trend of martian meteorites. On this diagram, most Earth basalts fall below the red line, and the Frass rock falls significantly distant from the line.

5.8 Rb vs. La

The proportion of rubidium to lanthanum, Rb/La, in basalts and their minerals differs from planet to planet (Laul et al., 1972b; Stolper et al., 1979; Wänke, 1981; McSween, 1985; Treiman et al., 1986). Rubidium and lanthanum behave nearly identically in the formation and crystallization of basalt lava – they are excluded nearly completely from solid minerals (olivine, pyroxenes, feldspars) and are concentrated together in the lava. Sometimes, a similar diagram is given as rubidium vs. uranium, as uranium and lanthanum behave the same in basalts. When a planet forms, lanthanum would have been more likely to accumulate onto the planet than rubidium (some of which would have remained in the gas). The Rb/La ratio would have not been affected by formation of a planet's core.

For basalts, abundances of Rb and La are usually given as mass in parts per million, ppm. Figure 5.8 shows that Rb and La abundances for the Frass rock plot with Earth basalts. The red line marks the Rb/La ratio for martian basalts. Some Earth basalts plot near or on this line, which means the Rb/La test is ambiguous – not all Earth basalts can be distinguished from Mars basalts using Rb and La. However, the Frass rock falls distinctly below the red line, suggesting that it is not from Mars.

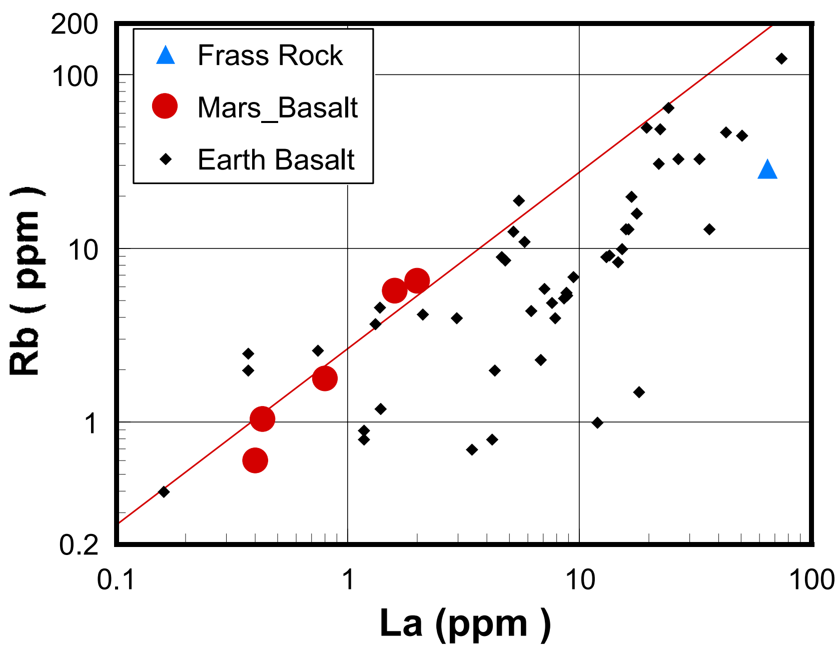

Figure 5.8. Abundances of rubidium (Rb) and lanthanum (La) in the Frass rock, martian meteorites, and reference basalts from Earth. The red line shows the Rb/La trend of martian meteorites. On this diagram, most Earth basalts fall below the red line, and the Frass rock falls far distant from the line. ALH84001 is anomalous on this diagram (as with Ni above) because it is not a basalt.

5.9 Cs vs. La

The proportion of cesium to lanthanum, Cs/La, in basalts and their minerals differs from planet to planet (Laul et al., 1972b; Stolper et al., 1979; McSween, 1985; Treiman et al., 1986). Cesium and lanthanum behave nearly identically in the formation and crystallization of basalt lava – they are excluded nearly completely from solid minerals (olivine, pyroxenes, feldspars) and are concentrated together in the lava. Sometimes similar data is given as cesium and uranium, as uranium and lanthanum behave the same in basalts. When a planet forms, lanthanum would have been more likely to accumulate onto the planet than Cesium (some of which would have remained in the gas). The Cs/La ratio would have not been affected by formation of a planet's core.

For basalts, abundances of Cs and La are usually given as mass in parts per million, ppm. Figure 5.9 shows that Cs and La abundances for the Frass rock graph with Earth basalts. The red line marks the Cs/La ratio for martian basalts. Some Earth basalts graph near or on this line, which means the test is possibly ambiguous – not all Earth basalts can be distinguished from Mars basalts using Cs and La. However, the Frass rock falls distinctly below the red line, suggesting that it is not from Mars.

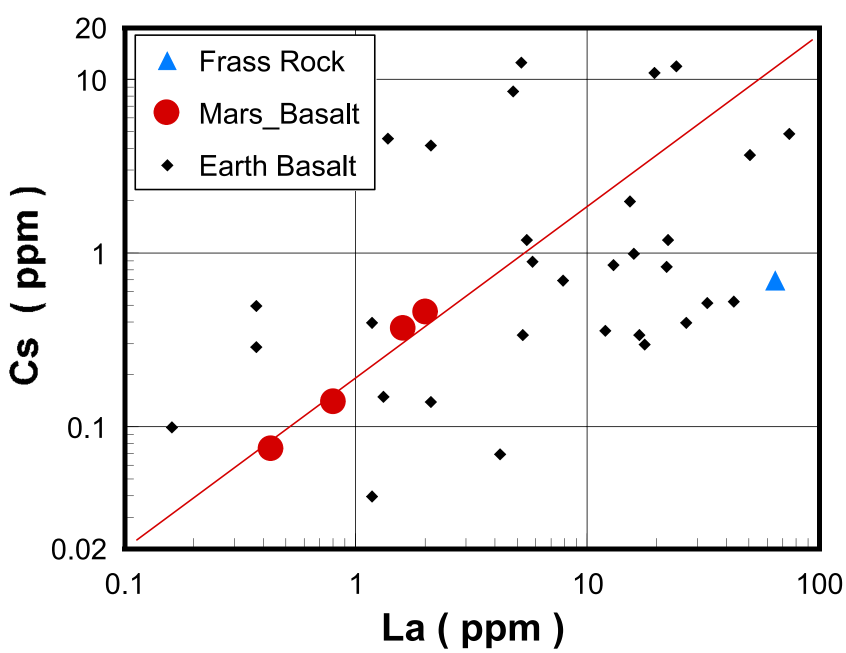

Figure 5.9. Abundances of cesium (Cs) and lanthanum (La) in the Frass rock, martian meteorites, and reference basalts from Earth. The red line shows the Cs/La trend of martian meteorites. On this diagram, Earth basalts scatter widely, but the Frass rock falls far distant from the martian meteorites.

5.10 Ga vs. Al

The proportion of gallium to aluminum, Ga/Al, in basalts and their minerals differs from planet to planet (Treiman et al., 1986; Drake et al., 1984; Drake and Malvin, 1987; Wänke and Dreibus, 1988). Gallium and aluminum behave nearly identically in the formation and crystallization of basalt lava – both elements are excluded from the minerals olivine and pyroxene in basalts, and both are strongly and similarly concentrated in the mineral feldspar; the result is that the proportion of gallium to aluminum changes little during melting or crystallization of basalts. When a planet forms, aluminum would have been more likely to accumulate onto the planet than gallium (some of which would have remained in the gas). When a planet's core forms, some of the planets' gallium goes into the core while no aluminum does.

For basalts, the abundance of Ga is usually given as mass in parts per million, ppm. For this graph, the abundance of Al is given as percent, not percent oxide. Figure 5.10 shows that Ga and Al abundances for the Frass rock fall with Earth basalts, and are not consistent with basalts from Mars.

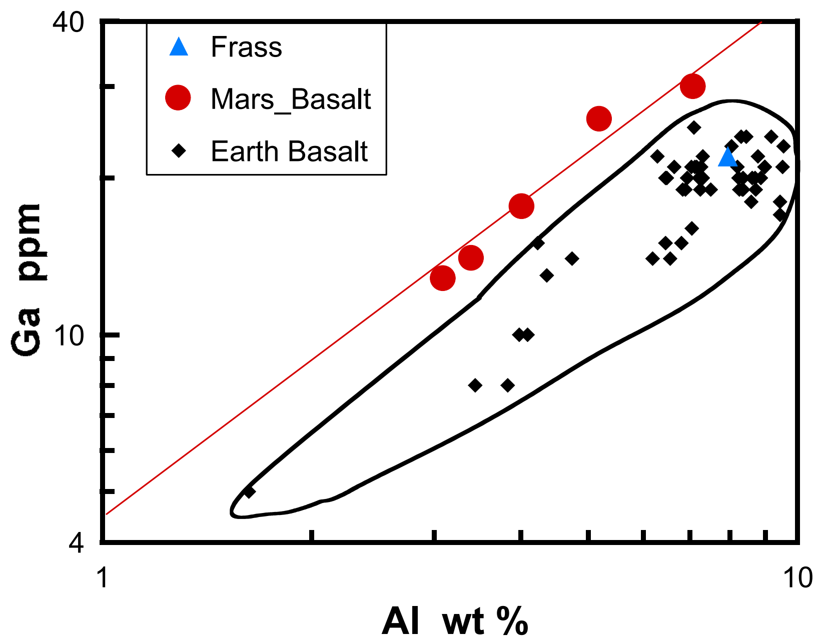

Figure 5.10. Abundances of gallium (Ga) and aluminum (Al) in the Frass rock, martian meteorites, and reference basalts from Earth. The red line shows the Ga/Al trend of martian meteorites; the black curve encircles Earth basalts. On this diagram, the Frass rock is identical to Earth basalts, and distant from martian basalts.

5.11 Ti vs. Al

Mars basalts contain significantly less aluminum than do Earth basalts; this difference has been tracked as the ratio of abundances of aluminum and titanium, Al_2O_3 vs. TiO_2 (Treiman et al., 1986). Aluminum and titanium behave similarly in basalt formation and early crystallization while olivine and pyroxene are the only crystalline minerals. When plagioclase begins crystallizing, the Al_2O_3 content of the lava stabilizes at ~ 15%. Finally, when the TiO_2 content of the lava reaches ~ 2%, iron-titanium oxide begins to crystallize and TiO_2 content starts to decrease. is present. These effects lead to arch-shaped trends of Figure 5.11. The Al/Ti ratio would have not been altered during formation of a planet or during formation of a planet's core.

Abundances of Ti and Al are given as weight percents of oxides in Figure 5.11. The Figure shows that the Frass rock has Ti and Al abundances squarely in the range of Earth basalts, and quite distinct from the range of Mars basalts. Note that a few Earth basalts have Al and Ti abundances like those of Martian basalts, but no martian basalts plot anywhere near the Frass rock.

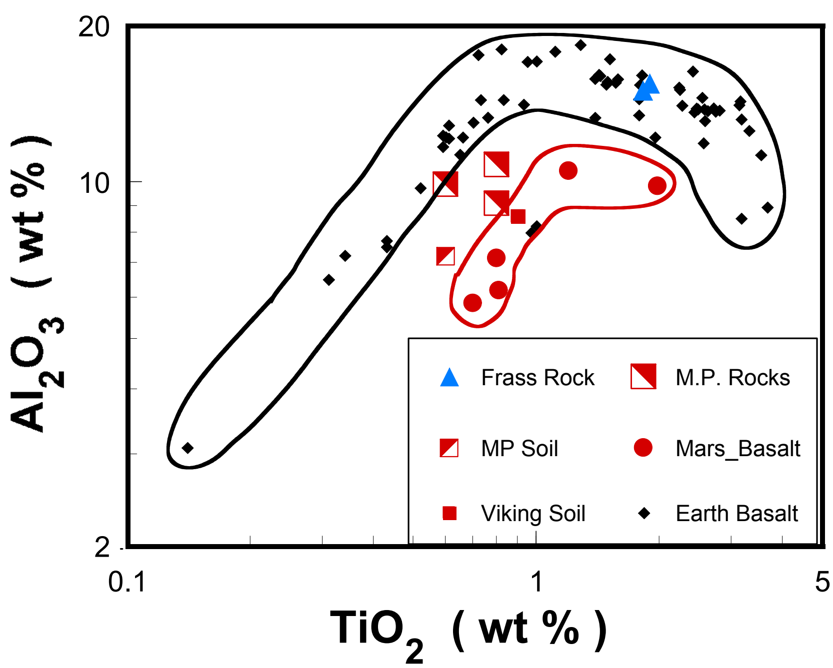

Figure 5.11. Abundances of aluminum (Al) and titanium (Ti), graphed as equivalent masses of the oxides Al_2O_3 and TiO_2, for the Frass rock, martian meteorite basalts (inside red line), rocks and soils at the Viking and Mars Pathfinder lander sites on Mars, and reference basalts from Earth (inside black line). The Frass rock falls in the trend of nearly all Earth basalts, and not in the area of martian materials.

6. Interpreting Analyses of Frass Rock "Sand"

Mr. M. Moore's letters to his Representative and Senators included a graph (top of page two of that letter) intending to show that the chemical composition of the Frass rock was consistent with a martian origin. Quoting his letters "I have done the testing, and the preliminary results indicate the rock is from Mars. No one will even discuss these tests with me…." His diagram, Mg/Si vs. Al/Si, is redrawn here as Figure 6.1 following Rieder et al. (1997) and section 5.6. On that graph, the analyses of "Frass sand" do plot in the area of Mars rocks, but one cannot conclude that the sand is from Mars. The "Mars" and "Earth" areas on this graph are NOT APPLICABLE to "sand," only to basalt lava rocks (or their close relatives).

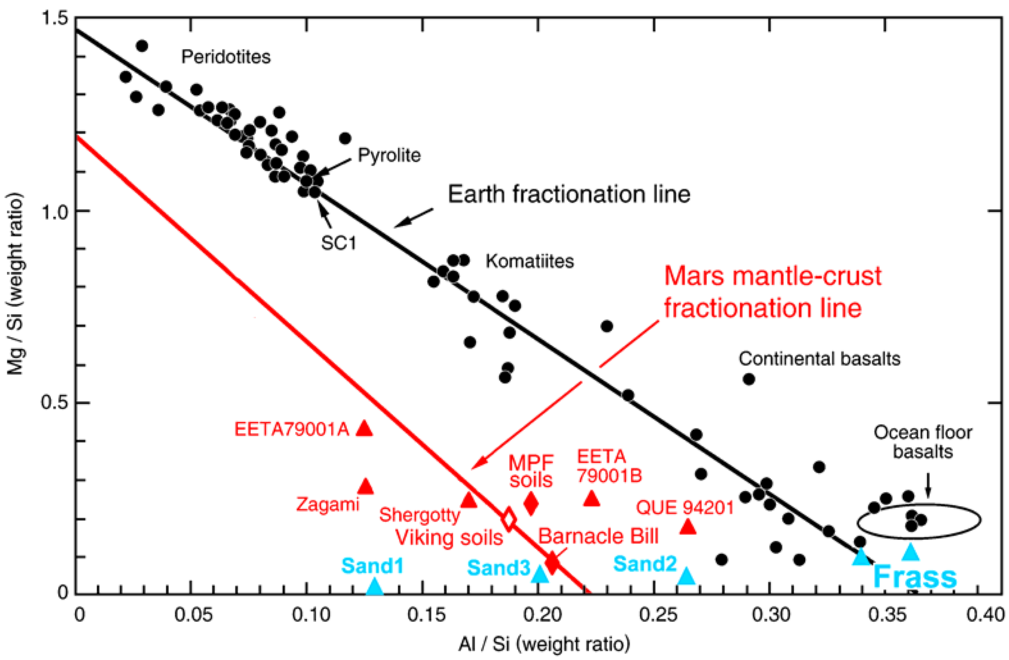

Figure 6.1. Frass analyses and sand graphed on Mg/Si vs. Al/Si (vis. Fig. 5.6). Note again that the Frass rock itself falls with Earth basalts. The "sand" analyses follow a trend from the rock toward the origin (0, 0) of the graph.

What are the "Frass sand" samples? Mr. Moore describes them as material fallen from the Frass rock, and material picked out of the holes in the rock. From my examination, this material consists of fragments of Frass basalt, grains of quartz sand, clay particles, and calcite (see Description above). The chemical analyses of the "sand" are consistent with this description. Figure 6.2 shows a standard diagram to interpret mixed samples – graphing element abundances (shown as equivalent oxides) against each other. If the samples are a simple mixture of two materials, abundances of each element ought to fall on a line connecting the abundances in the two starting materials. For the Frass rock, we do not know the composition of the "pure sand" component, and have to extrapolate to it. On Figure 6.2, note that the lines for the element oxides MgO, TiO_2, P_2O_5, and Fe_2O_3 pass through their 0% abundance level at an SiO_2 abundance of ~86%. Because a component of a real mixture cannot have negative abundances of elements, this compositions (the vertical dashed line) represents an extreme hypothetical “pure-sand” material. The composition of this material (caption of Fig. 6.2) is consistent with a mixture of quartz sand, clay, and calcite, as was found by microscopic study of the rock (Section 1 above).

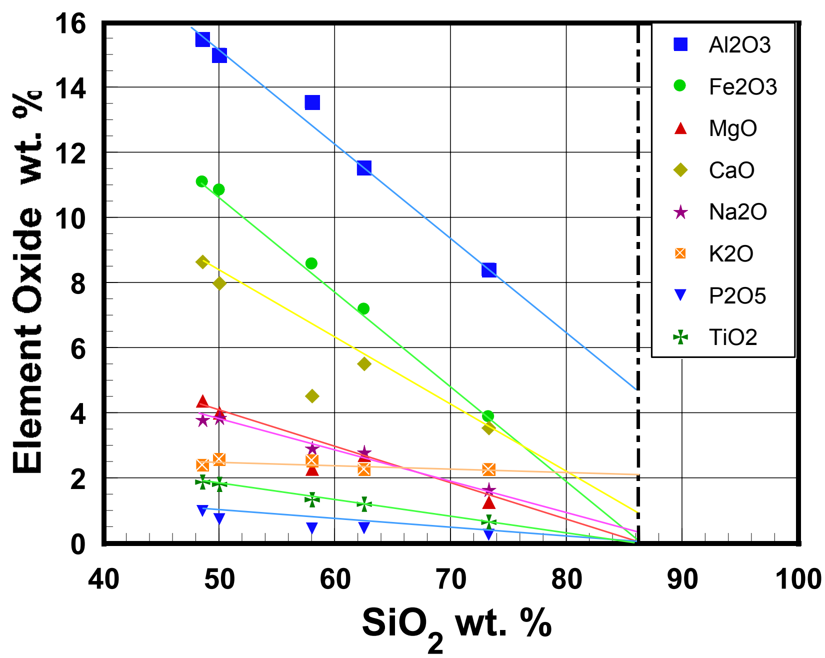

Figure 6.2. ‘Mixing’ analysis of chemical Analyses of Frass Rock and Sands. The extreme “pure sand” end of this mixture, the dashed line, is at the SiO_2 wt.% where the lines for Fe_2O_3, MgO, TiO_2, and P_2O_5 fall to zero. This “pure sand” would have had 5% Al_2O_3, 2% K_2O, 1% CaO, and 0.5% Na_2O.

Figure 6.3 is an expanded version of Figure 6.1, Mg/Si vs. Al/Si, showing in detail the Frass materials – at one end of the blue dashed line is the Frass basalt, and on the other end is a material with Mg/Si = 0 and Al/Si = 0.075 (quartz plus a little clay). To illustrate this point further, the dashed black line on Figure 6.3 shows hypothetical mixtures of an Earth basalt composition (labeled basalt) and pure quartz sand. The black dashed line extends from the basalt composition to the 0,0 point on the graph – pure quartz sand has lots of Si, but no Al or Mg. A mixture of 70% of this Earth basalt and 30% quartz sand falls near the “Mars Basalts” line, but is NOT a Mars Basalt.

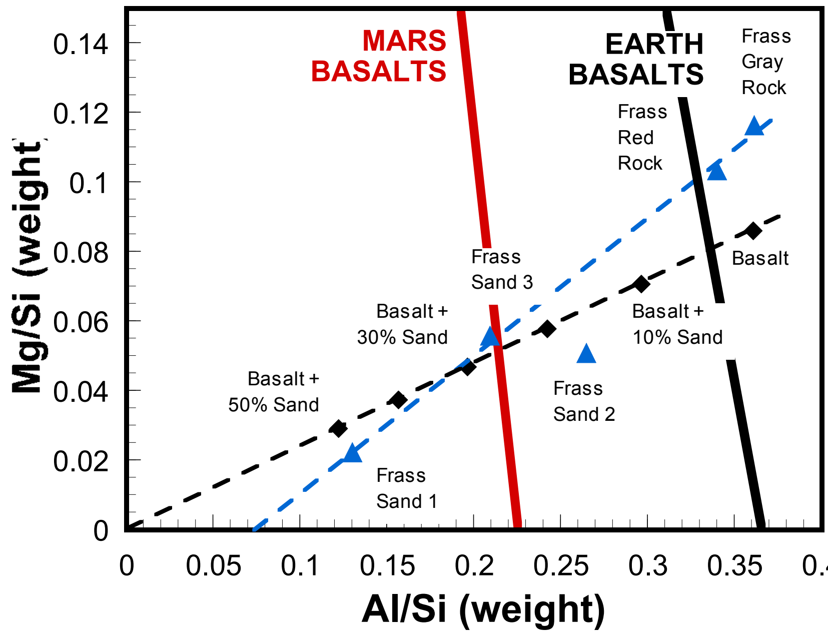

Figure 6.3. Expanded Mg/Si vs. Al/Si diagram. Blue points are analyses of Frass materials; blue line shows mixing of Frass basalt with a quartz+clay mixture. Black points show calculated compositions of mixtures of an representative Earth basalt (TP-1, from near Taos, NM; BVSP, 1981) with pure quartz sand. A mixture of 70% Earth basalt and 30% quartz sand appears nearly exactly on the Mars Basalt line, although it contains nothing from Mars.

7. Conclusions and Recommendations

The Frass rock cannot be considered a meteorite, in any normal sense of the term, as it shows no evidence of having come from beyond the Earth. It is not covered with a fusion crust, the melted layer that develops on rock meteorites as they pass through the Earth's atmosphere. If, indeed, the Frass Rock were a meteorite and had fallen the day before it was collected, it must show some evidence of its passage through the Earth's atmosphere. Nor does the chemical composition of the Frass Rock suggest an extraterrestrial origin. Every chemical test that could be applied is consistent with it having formed on Earth.

The Frass rock cannot be considered martian, based on our current knowledge of martian basalts. No test of the Frass rock's chemical composition requires that it be martian; every test is consistent with an Earthly origin.

At this time, I cannot recommend any further work be done on the Frass rock. Many other tests of martian origin are possible and could be done, for instance: oxygen isotope analyses, xenon isotope analyses, and further chemical analyses by neutron activation. However, the effort and expense of these additional tests are not justified, given the cumulative evidence here that the Frass rock formed on Earth.

8. Acknowledgments

Without the complete co-operation of Mr. Michael Moore, owner of the Frass rock, this investigation would not have been possible. Drs. D. Kring and J. Gleason (Univ. Arizona) supplied the thin section of the Frass rock. This work has benefited from the author's long professional associations with M. Lindstrom and J. Jones, both of NASA's Johnson Space Center. Funding for this work came through the Lunar and Planetary Institute, an independent non-profit organization committed to research and education in the space sciences. The Lunar and Planetary Institute is operated by Universities Space Research Associates under contract with NASA.

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10. Supplementary Material

Table 1. Major and Minor Element Analyses

	Red Rock	Gray Rock	Sand 1	Sand 2	Sand 3
SiO_2	50.00	48.54	73.26	58.00	62.50
TiO_2	1.82	1.89	0.66	1.35	1.21
Al_2O_3	15.00	15.48	8.40	13.55	11.54
Cr_2O_3	0.03	0.03	0.01	0.03	0.02
Fe_2O_3	10.85	11.10	3.89	8.58	7.19
MnO	0.12	0.13	0.05	0.08	0.09
MgO	4.01	4.38	1.27	2.29	2.71
CaO	7.99	8.65	3.55	4.53	5.52
Na_2O	3.87	3.81	1.66	2.93	2.81
K_2O	2.58	2.40	2.27	2.54	2.27
P_2O_5	0.75	1.00	0.27	0.46	0.47
LOI	2.77	1.57	4.08	5.79	3.17
Tot.	99.79	98.98	99.37	100.15	99.5
C	0.26			0.33	0.39
FeO	0.04			0.2	1.07
$-H_2O$	0.86			na	1.14
$+H_2O$	0.61			na	0.65
S	0.01			0.01	0.06
C(inorg)	0.1			0.05	0.15

All iron reported as Fe_2O_3, regardless of original oxidation state.
LOI = loss on ignition, or all combustible and volatile compounds, including water, organic and inorganic carbon. "$-H_2O$" is water adsorbed on minerals or held in them as water of hydration. "$+H_2O$" is structural water in minerals and glass, usually as OH^- ions or functional groups.

Table 2. Trace Element Abundances.

ppm	Red Rock	Sand 2	Sand 3
Co	31	22.5	19.5
Ni	60	60	40
Cu	25	25	5600
Zn	110	100	150
Ga	22	19	17
Rb	29	54.6	37.8
Sr	1620	1055	1035
Y	35.9	29	24.5
Zr	517	690	450
Nb	21	19	16
Ag	<1	<1	1
Sn	2	1	11
Cs	0.7	2.1	1.4
Ba	1380	1245	2900
La	64.5	48.5	42
Ce	132.5	103.5	88
Pr	16.4	12.6	10.9
Nd	67.5	46.5	44
Sm	12.1	9	6.6
Eu	3.2	2	6.4
Gd	10	6.4	4.8
Tb	1.2	1	0.9
Dy	7.1	5.1	4.4
Ho	1.1	1.1	0.8
Er	3.4	2.6	2.4
Tm	0.5	0.3	0.2
Yb	2.5	2.7	2.1
Lu	0.4	0.4	0.3
Hf	13	17	11
Ta	<1	<1	<1
Tl	<0.5	<0.5	<0.5
Th	2	2	1

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Allan H. Treiman
Mar. 22, 1999